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NEW DOUBLE-MODE AND OTHER RR LYRAE STARS FROM WASP DATA

WILS, PATRICK[1]

[1] Vereniging Voor Sterrenkunde, Belgium; e-mail: patrickwils@yahoo.com

The data from the first public data release of the exoplanet transit survey WASP (Wide Angle Search for Planets; Butters et al., 2010) were studied for a number of known and suspected RR Lyrae stars (types RR, RRab and RRc), and for a number of Horizontal Branch stars (Beers et al., 1988, 1996, Christlieb et al., 2005), in order to find previously unrecognized double-mode RR Lyrae (RRd) stars. In the analysis only TAMUZ (Collier Cameron et al., 2006) corrected data were used for which the uncertainty on the magnitude was less than 0.1. The period analysis was done using PERIOD04 (Lenz & Breger, 2005).

Seven previously unidentified RRd stars were found in this way: four among previously known RR Lyrae stars, and three more among the Horizontal Branch stars. Details of these seven stars are all listed in Table 1. After the name the WASP identification is given, followed by the full magnitude range (unfiltered WASP magnitude) and the periods of the fundamental and first overtone modes. The last column contains a sequence number used in Tables 2 and 3. These tables contain respectively the amplitudes and phases of the detected frequencies. Uncertainties are given between parentheses in units of the last decimal. These were calculated using the Monte Carlo simulations provided by PERIOD04. As is usual for RRd stars, the first overtone mode has a larger amplitude than the fundamental mode, except in the case of HE 0414-2958 = BPS CS 22182-17, in which both frequencies have similar amplitudes. As an illustration, phased light curves of V797 Her are provided in Fig. 1. Note also that BPS BS 16478-18 = BPS BS 16553-34 has a double identifier in Beers et al. (1996).

Among the 3670 Horizontal Branch stars from Beers et al. (1988, 1996) and Christlieb et al. (2005) for which there were enough WASP observations, 108 RRab, 77 RRc and 5 RRd stars were identified. Not all of these RR Lyrae stars are however new discoveries. Besides the three RRd stars from those catalogues mentioned in Table 1, also the RRd stars BS Com = BPS BS 15626-36 (Dékány, 2007) and GSC 7509-299 = BPS CS 22888-11 (Bernhard & Wils, 2006) were recovered. The relatively high number of RRc stars compared to the number of RRab stars may be a selection effect, as the objective prism and interference filter technique with which these stars were identified may favour the hotter RRc stars. For comparison, the Large Magellanic Cloud contains 17693 RRab, 4958 RRc and 986 RRd stars (Soszyński et al., 2009), while the Small Magellanic Cloud contains 1933 RRab, 175 RRc and 258 RRd stars (Soszyński et al., 2010).

For completeness, the other RR Lyrae stars found among the Horizontal Branch stars that were not included in the AAVSO Variable Star Index at the time of writing, are

Table 1: New double-mode RR Lyrae stars identified in WASP data.

Star	1SWASP	Range	P_0	P_1	N
UV Phe	J011210.74 − 411326.1	14.3-14.8	0.534254(5)	0.398668(1)	1
HE 0414-2958	J041649.58 − 295129.1	14.4-15.0	0.477467(6)	0.354824(4)	2
BPS BS 16478-18	J105743.63 + 384648.3	13.6-14.4	0.494909(14)	0.368498(5)	3
BPS BS 16466-19	J124322.85 + 345717.0	13.9-14.6	0.486651(2)	0.362228(1)	4
V633 Cen	J141302.53 − 434817.7	13.2-13.8	0.480517(3)	0.357379(1)	5
V797 Her	J171608.40 + 481752.7	14.2-14.9	0.532299(5)	0.397058(1)	6
NSV 12753	J200447.74 − 371503.4	14.7-15.1	0.474658(11)	0.353082(4)	7

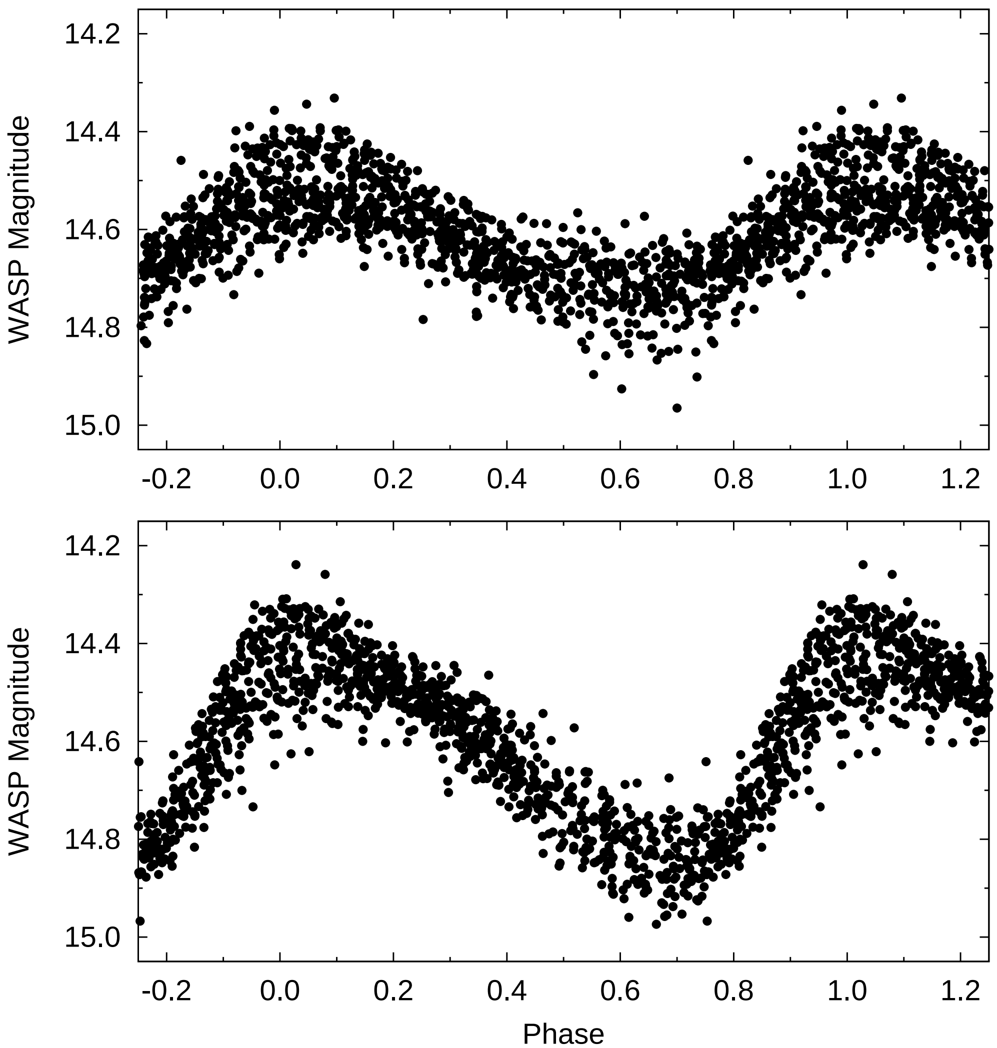

Figure 1. Light curve of V797 Her. Top: phased with the fundamental period and prewhitened with the first overtone mode and its harmonics. Bottom: as above, but now phased with the first overtone period and prewhitened with the fundamental mode and its harmonics. Each point is the average of 10 consecutive WASP observations.

Table 2: Semi-amplitudes of the frequencies detected in the WASP data of the new RRd stars. The number above each column refers to the stars in Table 1.

Freq.	1	2	3	4	5	6	7
f_0	0.074(2)	0.164(5)	0.164(3)	0.132(5)	0.118(2)	0.103(2)	0.053(4)
f_1	0.140(2)	0.158(5)	0.209(3)	0.188(4)	0.156(2)	0.200(2)	0.088(4)
$f_0 + f_1$	0.032(2)	0.071(4)	0.061(3)	0.057(4)	0.045(2)	0.041(2)	0.022(4)
$f_1 - f_0$	0.028(2)	0.048(5)	0.046(3)	0.041(5)	0.030(2)	0.035(2)	-
$2f_0$	0.010(2)	0.047(5)	0.027(3)	0.026(4)	0.023(2)	0.016(2)	-
$2f_1$	0.027(2)	0.034(4)	0.044(3)	0.028(5)	0.025(2)	0.044(2)	0.013(3)
$3f_1$	0.009(2)	-	-	-	0.009(2)	0.014(2)	-
$f_0 + 2f_1$	0.015(2)	0.025(5)	0.028(3)	-	0.018(2)	0.015(2)	-
$2f_0 + f_1$	-	0.025(5)	0.016(3)	0.020(4)	0.010(2)	-	-
$2f_0 + 2f_1$	-	-	0.018(3)	-	0.010(2)	-	-
$3f_0 + f_1$	-	-	-	-	0.006(2)	-	-

Table 3: Phases of the detected frequencies of the new RRd stars. These are given following the convention used by PERIOD04 and with T_0= HJD 2450000.

Freq.	1	2	3	4	5	6	7
f_0	0.077(4)	0.944(4)	0.032(3)	0.358(5)	0.393(3)	0.059(4)	0.916(9)
f_1	0.111(2)	0.678(4)	0.030(2)	0.346(4)	0.836(2)	0.767(2)	0.181(6)
$f_0 + f_1$	0.570(8)	0.002(12)	0.443(8)	0.106(12)	0.615(6)	0.229(9)	0.464(27)
$f_1 - f_0$	0.890(9)	0.624(17)	0.864(9)	0.896(16)	0.322(10)	0.558(10)	-
$2f_0$	0.491(28)	0.242(16)	0.443(16)	0.114(26)	0.156(13)	0.539(21)	-
$2f_1$	0.737(11)	0.869(22)	0.577(10)	0.265(22)	0.222(10)	0.076(7)	0.760(38)
$3f_1$	0.297(32)	-	-	-	0.519(27)	0.331(23)	-
$f_0 + 2f_1$	0.126(19)	0.139(32)	0.913(15)	-	0.910(17)	0.477(22)	-
$2f_0 + f_1$	-	0.360(28)	0.904(27)	0.929(33)	0.393(27)	-	-
$2f_0 + 2f_1$	-	-	0.440(22)	-	0.772(31)	-	-
$3f_0 + f_1$	-	-	-	-	0.379(48)	-	-

listed in Tables 4 (42 RRab) and 5 (46 RRc). When stars appear in two of the Horizontal Branch star lists, the designation of Christlieb et al. (2005) is given in the tables. Due to the fairly low resolution of the WASP instruments, in some cases the magnitude range and the WASP coordinates may be affected by nearby stars.

A Petersen diagram of all known Galactic RRd stars is plotted in Fig. 2. Apart from the stars from Table 1 and those listed in the references cited by Dékány (2009), the RRd stars given by Wu et al. (2005), Gruberbauer et al. (2007), Pilecki & Szczygieł (2007), Szczygieł & Fabrycky (2007), McClusky (2008), Sokolovsky et al. (2009) and Khruslov (2010) are included, 75 in total. In addition the brightest RRd stars with respectively $I < 18.0$ and $I < 18.5$ in the LMC and SMC catalogues (Soszyński et al., 2009 and 2010) were considered to be Galactic foreground objects. This gives 14 additional stars (7 from each of the LMC and SMC lists).

Three Galactic RRd stars have a higher period ratio than what can be expected from the other stars. The one with the highest ratio, [C2001c] vd05f715 (Cseresnjes, 2001), has noisy data, so that one of the frequencies may well turn out to be spurious. [1] The limited number of data points for [IGF2000] 91 (Wu et al., 2005) may have resulted in inaccurate frequencies as well. The most interesting of the outlier objects is likely OGLE BUL-SC39 V1568 (Mizerski, 2003), as the OGLE II data (Udalski et al., 1997 and Szymański,

[1] In fact the MACHO data for this object (MACHO 122.23470.655; Allsman & Axelrod, 2001) show it to be a contact binary with a period of 0.8309d, twice the period of the first overtone mode given by Cseresnjes (2001).

Table 4: New RR Lyrae stars pulsating in the fundamental mode (RRab) identified in WASP data among Field Horizontal Branch Stars (Beers et al., 1988, 1996, Christlieb et al., 2005). The epoch of maximum is given as HJD - 2450000. The letter B at the end of the line denotes stars that show the Blazhko effect.

Star	1SWASP	Range	Period	Epoch	
BPS CS 22876-029	J000157.75 − 364042.4	13.5-14.0	0.63752	4001.56	B
HE 0001-4300	J000400.87 − 424356.7	14.3-14.8	0.51895	3880.61	
HE 0007-3416	J000944.08 − 335920.1	13.9-15.0	0.60493	4270.57	
HE 0147-3030	J014926.72 − 301600.0	14.0-15.2	0.57693	3981.48	
HE 0155-2108	J015744.41 − 205346.5	14.7-15.0	0.35943	4379.60	
HE 0200-4322	J020236.92 − 430755.8	14.6-15.0	0.67014	3999.57	
HE 0210-3735	J021237.64 − 372112.7	13.6-13.8	0.50770	4050.38	
HE 0314-2836	J031616.36 − 282534.8	14.2-14.5	0.59432	4090.31	
HE 0332-2129	J033419.05 − 211959.8	14.4-15.2	0.54191	4353.56	B
HE 0333-4650	J033452.98 − 464023.5	13.9-14.8	0.48951	4484.32	B
HE 0441-3136	J044255.90 − 313118.3	14.8-16.3	0.34337	4412.44	
HE 0443-2513	J044505.91 − 250823.0	15.0-15.3	0.32996	4110.35	
HE 0504-3113	J050606.02 − 310953.5	14.2-14.7	0.56835	4136.41	
HE 0510-4101	J051207.76 − 405759.8	14.5-15.1	0.68467	4029.44	
HE 0549-3927	J055104.65 − 392620.9	14.8-15.4	0.56970	4522.28	
HE 1015-2201	J101812.69 − 221619.7	14.2-15.0	0.56692	4522.48	
HE 1104-3222	J110703.96 − 323902.0	14.0-14.4	0.56947	3862.05	
BPS BS 16545-047	J111329.97 + 353434.7	13.1-13.3	0.45695	4140.71	
HE 1111-2927	J111352.38 − 294334.3	14.8-14.9	0.47236	4155.51	
HE 1112-1950	J111451.40 − 200704.1	15.0-15.4	0.30855	4564.38	
HE 1157-2813	J115953.34 − 282929.3	13.6-13.9	0.52957	3898.24	
HE 1157-2519	J115958.37 − 253547.3	14.5-14.7	0.51239	3890.22	
HE 1233-2316	J123636.50 − 233238.7	14.9-15.4	0.60441	4586.24	
HE 1239-2151	J124201.81 − 220748.5	12.4-12.5	0.55074	4495.54	
HE 1338-2727	J134100.84 − 274233.2	14.2-15.1	0.62896	4562.38	
HE 1351-2348	J135421.23 − 240323.4	14.0-14.8	0.46064	4588.43	
HE 1354-2320	J135702.57 − 233448.1	14.6-15.1	0.60405	4562.50	
HE 1358-2125	J140049.44 − 214009.5	13.9-15.1	0.47163	4572.53	
BPS BS 16554-067	J140655.96 + 205658.6	13.6-13.7	0.33906	4261.54	
BPS CS 22936-279	J190129.86 − 354511.2	13.8-14.2	0.64767	4250.67	
BPS CS 22885-084	J202501.21 − 422417.9	14.4-14.6	0.49462	4387.26	
BPS CS 22955-119	J203041.85 − 235720.2	14.1-14.7	0.60865	3960.46	B
BPS CS 22955-139	J203637.65 − 240537.0	13.7-15.1	0.46782	4301.35	
BPS CS 22880-004	J203911.98 − 212449.7	13.6-14.4	0.61036	3891.58	
BPS CS 29501-046	J211204.06 − 370008.1	14.0-14.8	0.54534	4271.70	
BPS CS 22948-023	J213530.97 − 390630.5	14.5-15.0	0.57652	4300.53	B
BPS CS 22948-084	J214600.39 − 401553.4	14.0-15.0	0.66984	4300.39	
HE 2150-3053	J215320.37 − 303914.1	14.1-14.7	0.64148	3960.32	
HE 2217-3717	J222042.00 − 370204.2	15.1-15.2	0.55321	3999.29	
HE 2317-4517	J231959.89 − 450045.8	14.1-14.3	0.62527	3954.56	
HE 2325-4624	J232746.99 − 460800.7	14.4-15.0	0.29106	3909.61	B
BPS CS 22876-023	J235742.03 − 340111.2	14.4-15.2	0.27802	3953.60	

Table 5: New RR Lyrae stars pulsating in the first overtone mode (RRc). For details, see Table 4.

Star	1SWASP	Range	Period	Epoch	
BPS CS 29509-039	J005441.47 − 281354.6	14.0-14.2	0.27286	4083.31	
HE 0055-3951	J005749.63 − 393531.4	14.0-14.4	0.36111	4041.51	
HE 0145-2946	J014754.61 − 293131.2	14.5-14.9	0.34140	4000.45	
HE 0222-2507	J022440.34 − 245403.6	14.7-15.1	0.29095	3996.58	
HE 0250-3150	J025212.05 − 313827.5	14.8-15.2	0.29625	4007.53	
HE 0311-2333	J031347.95 − 232239.6	14.4-14.8	0.33963	4353.55	
HE 0351-3512	J035256.91 − 350327.9	14.7-15.2	0.30276	4421.28	
HE 0428-3926	J042952.36 − 392004.6	13.7-13.8	0.27715	4488.35	
HE 0442-3801	J044357.89 − 375609.2	14.2-14.5	0.27606	4444.55	
HE 0505-3833b	J050712.81 − 382956.0	14.0-14.2	0.27391	4454.30	
BPS BS 16473-027	J084337.67 + 465824.3	14.6-14.9	0.28122	4501.39	
BPS BS 16468-023	J090600.07 + 392758.6	14.0-14.4	0.35638	4092.66	
BPS BS 16468-121	J092321.37 + 383836.6	14.6-15.0	0.29065	4157.65	
BPS BS 16927-028	J093240.67 + 422108.4	12.2-12.6	0.25399	4533.39	
HE 1046-2228	J104833.88 − 224414.8	14.5-14.9	0.33384	4110.55	B
BPS BS 16478-017	J105520.01 + 383039.0	14.3-14.8	0.27416	4203.42	
BPS BS 16545-066	J112042.66 + 344712.6	12.7-13.0	0.33970	4168.41	
HE 1122-2844	J112439.10 − 290048.2	13.9-14.2	0.37957	4572.13	
BPS BS 16077-009	J113525.85 + 304318.1	13.3-13.7	0.31215	4167.42	
HE 1222-2649	J122535.83 − 270549.7	14.3-14.8	0.33595	4572.50	
HE 1228-2341	J123046.18 − 235743.6	14.7-14.9	0.30872	4558.58	
BPS BS 16032-029	J124643.41 + 282809.8	14.1-14.6	0.35752	4216.63	
HE 1302-2257	J130442.80 − 231336.6	13.8-14.2	0.27356	4554.32	
BPS BS 16938-029	J130508.41 + 391533.1	14.5-14.9	0.31621	3153.38	
BPS BS 16076-087	J130753.93 + 221007.1	14.0-14.5	0.40112	4218.38	
BPS BS 15623-004	J141022.29 + 254433.1	14.3-14.6	0.34471	4216.42	
BPS BS 16084-087	J161635.47 + 542258.4	12.0-12.3	0.30627	4626.60	
BPS CS 22936-325	J190329.08 − 332433.8	14.1-14.4	0.31945	3919.59	
BPS CS 22955-036	J202146.61 − 234129.5	14.3-14.5	0.38810	4002.28	
BPS CS 22943-115	J202210.82 − 451849.2	13.4-13.5	0.32715	3897.43	
BPS CS 22885-200	J202301.74 − 415448.5	14.8-15.0	0.31697	4272.51	
BPS CS 22955-094	J203037.02 − 271349.3	14.9-15.1	0.26593	4592.52	
BPS CS 22880-076	J204825.07 − 204635.4	14.5-14.9	0.27237	4361.27	
BPS CS 29501-083	J211730.39 − 351757.9	14.9-15.2	0.36968	4292.43	
HE 2115-4535	J211910.34 − 452233.7	14.5-14.9	0.30140	3999.35	
HE 2126-4428	J213012.04 − 441520.4	13.9-14.5	0.30029	4238.60	
BPS CS 29495-050	J214006.88 − 265319.3	14.3-14.7	0.32103	4296.67	
BPS CS 29495-090	J214935.24 − 233018.7	13.9-14.2	0.26758	3925.49	
BPS CS 22951-097	J215736.58 − 453236.0	13.9-14.2	0.31660	4364.42	
HE 2201-2717	J220442.48 − 270233.3	14.3-14.9	0.29918	3965.34	
HE 2309-3753	J231214.23 − 373719.5	14.6-15.1	0.29260	4273.54	
HE 2316-3757	J231917.06 − 374047.9	13.7-14.1	0.34475	4338.42	
BPS CS 29496-026	J234648.67 − 300028.7	14.5-15.0	0.29756	3943.60	
HE 2344-2511	J234735.06 − 245507.8	14.1-14.4	0.37096	4352.52	
HE 2349-4236	J235223.86 − 422000.8	14.7-15.0	0.26362	3919.53	
HE 2356-4456	J235856.59 − 444014.6	14.4-14.8	0.33155	3953.54	

2005) for this object show additional frequencies very close to the main ones, an indication of a rapidly changing period. In that case, the period ratio may not be reliable. More observations of this object are highly recommended.

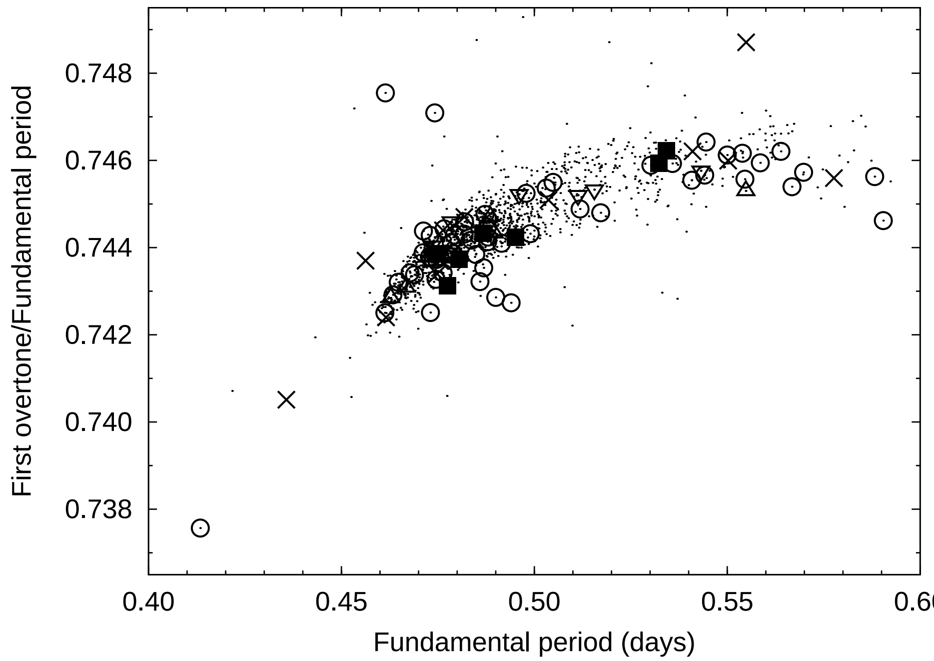

Figure 2. Petersen diagram of 89 Galactic RRd stars. The stars from Table 1 are shown as black squares, foreground stars to the LMC and SMC as up- and downward pointing triangles resp., the Sgr foreground stars (Cseresnjes, 2001) as crosses, and other previously known RRd stars as open circles. For comparison, the RRd stars of the LMC and SMC (Soszyński et al., 2009, 2010) are plotted as small dots.

The distribution of the periods of the Galactic RRd stars in Fig. 2 appears to be bimodal, with the majority of stars having a fundamental period around 0.48 days, a lack of stars with periods around 0.52-0.53 days and a substantial number of stars with periods around 0.55 days. This is clearly evident as well when comparing the cumulative distribution of the Galactic RRd stars with those from the Large and Small Magellanic clouds (Soszyński et al., 2009, 2010) in Fig. 3. Although there is a small increase of SMC RRd stars with a period near 0.56 days, this increase is less pronounced than in the Galactic case. The LMC does not show this bimodality.

Because many of the Galactic RRd stars have been found in data from surveys that make at most a few observations per night, the apparent lack of RRd stars with a fundamental period near 0.52 days (or a first overtone period near 0.39 days) could be attributed to a selection effect. However it is more likely that variable stars with a period very close to an integer fraction of a day (e.g. 0.50 or 0.33 days) would go undetected. Also the RRab stars found in data from the Northern Sky Variability Survey (Wils et al., 2006 and Kinemuchi et al., 2006) do not show fewer stars with periods near 0.39 or 0.52 days. But the sample of Galactic RRd stars is certainly not a homogeneous sample as is the case for those found in the Magellanic Clouds, so this will need to be explored further. In addition, the relative number of known RRd stars with respect to RRab or RRc stars is still relatively small in the Galaxy compared to those in the Magellanic Clouds.

The RRd stars in the Sagittarius dwarf galaxy (Cseresnjes, 2001) show a similar bimodal distribution (Fig. 3). In this case the gap is symmetrically located around a fundamental period of 0.50 days, so that this could really be a selection effect as described above. But again, the distribution of periods of RRab stars in the same field does not show a lack of stars with periods around 0.50 days (Cseresnjes et al., 2000). Also the double-mode RR Lyrae stars in the Sculptor dwarf galaxy (Kovács, 2001) show a bimodal distribution, but with only 18 objects (including only two stars with a longer period) this sample is too small for definite conclusions.

The globular cluster IC 4449 contains only 13 short period RRd stars, while the 9 in M68 and the 8 in M15 have long periods (Clement et al., 1993). This could be explained in terms of the Oosterhoff dichotomy for those globular clusters (Oosterhoff 1939), with longer period stars in metal-poor Oosterhoff type II clusters, and shorter period stars in relatively metal-rich Oosterhoff type I clusters. The RRab population in the solar neighbourhood has been described as a mixture of metal-rich (Thick Disc), Oosterhoff I, and Oosterhoff II stars (Kinemuchi et al., 2006). The bimodality in the period distribution of Galactic Field RRd stars may also be a consequence of this.

In Fig. 3 also an obvious shift of about 0.02 days can be seen between the average periods of the RRd stars in the SMC and the other galaxies (the LMC in particular). The difference of the mean RRd period between the LMC and SMC is significant to better than the 99% confidence level. It may be due to the different metallicities of stars in the Magellanic Clouds. Dékány (2009) derived tight relations for the radius and density of double-mode RR Lyrae stars as a function of their fundamental period. Based on the longer period of the SMC stars, these relations indicate a higher mass, and from Dékány's (2009) mass-metallicity graphs also a lower metallicity on average for the SMC, as is generally accepted.

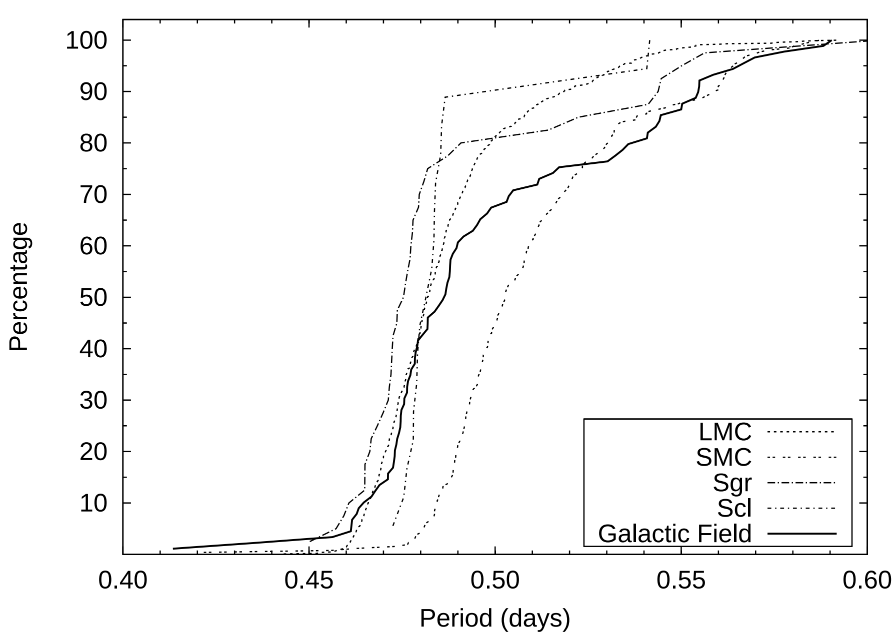

Figure 3. Cumulative distribution of the periods of the fundamental mode of the double-mode RR Lyrae stars in the Magellanic Clouds (Soszyński et al., 2009, 2010), in the Sagittarius (Cseresnjes, 2001) and the Sculptor dwarf galaxies (Kovács, 2001) and in the Galactic Field.

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